Power generation system for l-moxie: Concept proposal and trade-off analysis

Power generation system for L-MOXIE: concept proposal and trade-off analysis

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The manned exploration of Mars is a demanding goal, requiring a large amount of resources. Among them, oxygen is without doubt pivotal since it is needed for the crew to breathe and for the Mars Ascent Vehicle to fuel the return journey to the Earth. In light of this, In-Situ Resource Utilization (ISRU) practices become useful. We know that carbon dioxide constitutes about 96% of Martian atmosphere and it is the candidate for oxygen extraction through a Solid Oxide Electrolysis reaction. The Mars Oxygen ISRU Experiment (MOXIE) demonstrator proved this concept on board of the Perseverance Rover in April 2021. A full-scale device suitable for a human mission, called L-MOXIE, will be more than 200 times larger. In this work, we evaluate the power requirements of L-MOXIE leveraging a process simulation developed in Aspen Hysys, obtaining a consumption of $22.8\,\mathrm{kW}$. This result suggests a thorough redesign of the power generation system. To perform this design activity, we employ a forcing technique based on C-K theory pillars to broaden the spectrum of options retrieved from the literature review. Our degrees of freedom are the power generation technology, the power transmission system and the power storage system while the constraints are set forth by the Martian environment, the oxygen handling and maintenance, and by the safety and maintenance. From the partial solutions, we build a morphological chart, and three concepts are then generated based on nuclear, grounded solar, and orbiting photovoltaic Power Generation System. We performed a Multi-Attribute Utility Analysis (MAUA) to assess them, and the nuclear and grounded solar concepts proved more attractive than the orbiting photovoltaic concept. These results will serve for a number of activities outside the scope of this paper, such as a feasibility analysis and a multi-objective optimization for the nuclear and grounded solar concept.

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I. Introduction

In recent years, the plans to colonize Mars are gaining significant publicity. However, a human mission to Mars requires a large deal of resources and raw materials to be employed and processed. Basic needs for human survival and colonization are for instance water refurbishment and habitat modules construction. All those activities demand for raw materials and energy whose direct supply from the Earth would be unavoidably limited, discontinuous, and dramatically expensive, therefore unfeasible. To overcome these limitations, In-Situ Resource Utilization (ISRU) practices aim at exploiting materials and resources locally available and transforming them into ready-to-use products. Among those, oxygen is one the of the most demanded elements: indeed, oxygen would be essential to support basic life functions of the human crew (breathing), and to fuel the Mars Ascent Vehicle (MAV) [1] that leaves the Mars surface to bring the crew and the payload back to Earth.

From investigations and explorations of the Red Planet, we learned that only the 0.2% of the Mars atmosphere is oxygen, while carbon dioxide constitutes about 96% which makes it a better candidate for oxygen extraction. The Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE) technology has been recently developed to extract the oxygen from carbon dioxide [2]: the prototype is currently on board the Perseverance Rover for TRL8 in-situ demonstration [3]. This device converts the CO_2 available in the atmosphere into O_2 through a Solid Oxide Electrolysis reaction that requires an external energy supply. A Multi-Mission Radioisotope Thermoelectric Generator converts the heat from the plutonium decay into electricity and ensures the power supply of 0.3 kW to produce 10 g/h of oxygen. The MOXIE is the demonstration experiment for a scaled-up system, the L-MOXIE, designed to supply tens of tons of oxygen to fill the Mars Ascent Vehicle tanks for a manned mission [4]. The L-MOXIE will be almost 200 times larger than the actual one and the power requirement is expected to be between 25 kW and 30 kW [5]. The power generation technology currently employed for the MOXIE is inadequate for the energy-intensive device scaled to support MAV operations.

This paper presents advances of the MAV-Ops project that brings together an international team across three institutions (Politecnico di Torino, Politecnico di Milano, MIT) to design and assess multiple power generation systems for the L-MOXIE, targeting a possible MAV launch to occur between 2030 and 2035. To design the system, we employ a forcing technique based on C-K theory pillars in order to find several potential design options. We then leverage a morphological chart to build a number of concepts. We evaluate the selected alternatives through the MAUA analysis introducing the evaluation metrics such as weight, safety, deployability, compactness and TRL of the power generation.

In particular, we propose and compare three concepts for power generation systems: (i) the Kilopower nuclear reactor, (ii) the ground based solar panels, (iii) the orbiting photovoltaic panels. The Kilopower reactor is currently investigated by NASA through the KRUSTY experiment [6]; it has a fissile nucleus of enriched uranium and is based on Stirling engines to produce electricity. Instead, the solar panels are a mature technology and their application is common on Martian landers and rovers. We address the open challenge of installing a photovoltaic power plant on the Martian soil. The third concept relies on orbiting photovoltaic panels to overcome the intermittent energy supply of conventional solar panels, caused by day-night cycles. The strengths and weaknesses identified for each concept are discussed to support decision-making on technology development strategies and design alternatives, towards reliable electric power generation systems for a future human settlement on the Red Planet.

This paper is structured as follows. In Problem Setup, we introduce the main constraints and degrees of freedom at stake. We model the L-MOXIE in Aspen Hysys and, applying the scale-up criteria, we are able to assess the overall power consumption. In Methods, we describe the tools employed to generate the concepts. These are the forcing technique based on C-K theory pillars and the morphological chart. Moreover, we focus on the Multi-Attribute Utility Analysis (MAUA), that is used as a scoring method. In Results, we present the three concepts, their assessment and their discussion. Finally, we summarize the main findings with a focus on possible follow-up activities.

II. Problem Setup

The problem consists in designing possible concepts to produce a sufficient amount of electricity to power the L-MOXIE. This device aims at producing the Liquid Oxygen (LOX) used as propellant for the return voyage of the MAV. Assuming a crew of four, 22.72 t of LOX are needed [7]. The L-MOXIE should produce this amount of oxygen in 14 months, which means a constant oxygen production of 2.22 kg/h. To fulfill this requirement, we generate conceptual proposals which include systems for power generation, transmission, storage, oxygen handling, and for the ancillary facilities.

To set the boundaries of the problem, we analyse the main factors to which systems on Mars are subjected. In this way, we identify the main factors affecting the functionalities of the global system. We group these factors in macro-clusters that we considered uncoupled in the very first analysis. These are: (i) Martian environment, (ii) Power generation technology, (iii) Power transmission system, (iv) Power storage system, (v) Oxygen handling and storage, (vi) Safety and maintenance. The macro-clusters that we identify are constraints that must be respected or parameters that are not specified and become degrees of freedom to be fulfilled during the design process.

We identify the Martian environment, the oxygen handling and storage, the safety and maintenance as constraints. On Mars, there are several aspects which create potential hindrances to any design activity. For instance, the Martian climate, with average temperatures of $-63\,°C$ [8], and average pressure of 6.3 mbar [9], the wind, reaching even $30\,m/s$ during dust storms [10] and the dust, which interferes with the instrumentation sent on the Red Planet [11] [12]. The degrees of freedom that we identify are the power generation technology, the power transmission system and the power storage system. We estimate the power consumption of the L-MOXIE through numerical modelling, and this parameter constitutes the design basis for the concepts generation activity.

A. L-MOXIE modelling in Aspen Hysys

The recent data available from the experimental run of MOXIE [2] are exploited to build a finer model for the power requirement estimation of the L-MOXIE. In fact, the studies found in literature estimate the power consumption based on the design values instead of the experimental ones which were not available at that time [13] [14] [15] [16]. In this work, we model the L-MOXIE leveraging the process simulator Aspen Hysys. This tool allows the steady-state simulation of chemical processes performing detailed mass and energy balances. The data available from the MOXIE test run, where 6 g/hour are produced [2], are rearranged to ease the power estimation. The obtained contributions are reported in Table 1. In particular, the heaters' power is broken down in two terms, distinguishing between the heat needed to pre-heat the inlet gas and the heat dissipated through conduction and radiation from the hot-box. The pre-heating power is estimated through the energy balance written in Equation 1, where $Q_{PreHeat}$ indicates the power to preheat the cold feed up to the operating temperature, $H_{Effluents}$ indicates the enthalpy of the hot gas discharged from the MOXIE, H_{Feed} indicates the enthalpy of the cold gas fed to the MOXIE and $Q_{Electrolysis}$ indicates the power supplied to the stack for the chemical conversion. The control volume corresponds to the hot-box which is considered adiabatic.

$$Q_{PreHeat} = H_{Effluents} - H_{Feed} - Q_{Electrolysis} \tag{1}$$

The enthalpy of the streams involved in the MOXIE run are rigorously calculated exploiting the Aspen databank. The Peng-Robinson equation of state which is employed is suitable for non-condensing gases. The pre-heating power is equal to 15 W and the heat losses due to conduction and irradiation are equal to 71.9 W. This subdivision is aligned with the preliminary estimations [17]. The power consumption of sensors, transducers and electronics are grouped together and they are equal to 28.3 W. This contribution does not include the consumption of the DC converter.

MOXIE Power Consumption	
Contribution	Consumption [W]
SOXE Electrolysis	29.2
Compressor	106.0
Pre-Heating	15.0
Heat Losses	71.9
Electronics, Transducers, Sensors	28.3
Total Power	250.4

Table 1 Rearranged power contributions of the experimental MOXIE test-run.

The process scheme of our L-MOXIE simulation is reported in Figure 1. Here the boundary conditions of the simulation are those found on Mars and not anymore the ones of the MOXIE test-run. The intensive and extensive properties of the inlet stream (L1) are fully characterized assuming the average Martian properties reported in the problem setup. To determine the flowrate of L1, the CO_2 fraction utilization, also known as conversion, is assumed equal to X=45%. In this condition no fouling of the electrolyzer is observed [18]. Considering the stoichiometry of the electrolysis reaction, the calculated inlet flowrate is L1=14.07 kg/h. The filter is modelled in Aspen Hysys as a throttle valve to keep the focus on pressure drops only and not on filtration capabilities. Experimental evidence shows that a HEPA filter for this application has a pressure drop around 0.50 mbar [19].

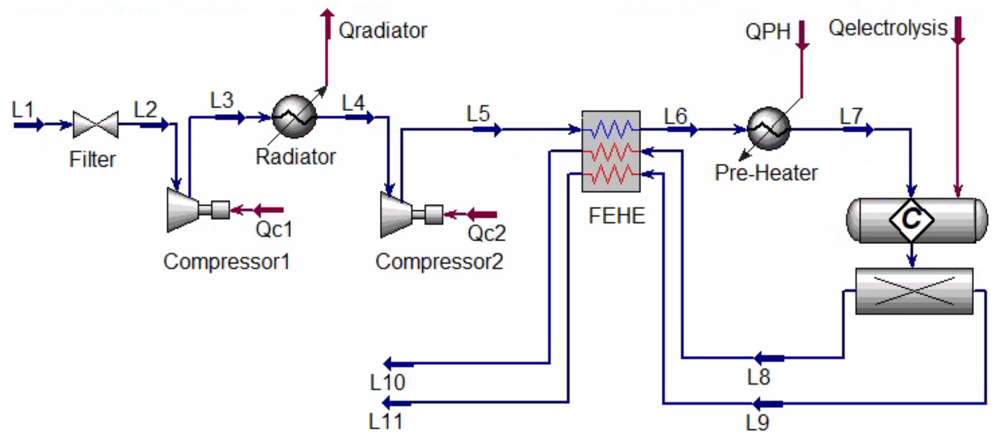

Fig. 1 Process scheme of the L-MOXIE simulated in Aspen Hysys. It includes the filter, two stages of compression, the radiator, the FEHE, the pre-heater and the electrolyzer.

The compression step occurs after the filtration. The most important parameter that determines the compressor's consumption is the isentropic efficiency. This parameter cannot be retrieved from the MOXIE experiment because in that case an orifice is installed downstream to conclude the process with an isochoric transformation. This strategy requires much more power than simple compression [20]. In this simulation a reliable estimation of the isentropic efficiency is retrieved from the data reported by Air Squared, the manufacturer of the MOXIE scroll compressor [21]. A conservative value of 55% is considered. The arrangement proposed in this work is a two-stage scroll compressor with an intercooling done with a radiator. This configuration reduces significantly the power requirements [17] if compared to the scale-up of a single stage compressor [5]. The final discharge pressure is assumed equal to the MOXIE design value of 760 Torr [4]. After the compression, a Feed-Effluent Heat Exchanger (FEHE) is introduced to recover the heat from the products. The pre-heater introduces the remaining heat to raise the gas temperature up to 800 °C. The electrolyzer is modelled as a reactor and a splitter, assigning the temperature, the CO_2 fraction utilization, and the pressure drop. The results obtained from the simulation of L-MOXIE are reported in Table 2.

Simulation results: Power	
Duty	Consumption [kW]
Q_{c1}	1.000
Q_{c2}	1.276
$Q_{radiator}$	0.797
Q_{FEHE}	1.817
Q_{PH}	0.251
$Q_{Electrolysis}$	10.899

Table 2 Equipment duties evaluated through the Aspen Hysys simulation.

B. L-MOXIE power consumption estimation

We perform an independent estimation of the power requirements for the L-MOXIE together with the oxygen liquefaction and storage system. The steady-state portion of the MOXIE test-run is considered for the power requirements estimation [2], since the L-MOXIE is expected to run continuously for 14 months. We assume that the start-up and shut-down phases do not affect the system's sizing. Leveraging the process modelling in Aspen Hysys and applying the scale up criteria, we estimate an overall power consumption of 22.8 kW for the full scale system. A visual representation of the power contributions is given in Figure 2. This value is the design specification for the concepts proposed in this work. The overall consumption is the summation of seven items which scale-up differently depending on their physical nature.

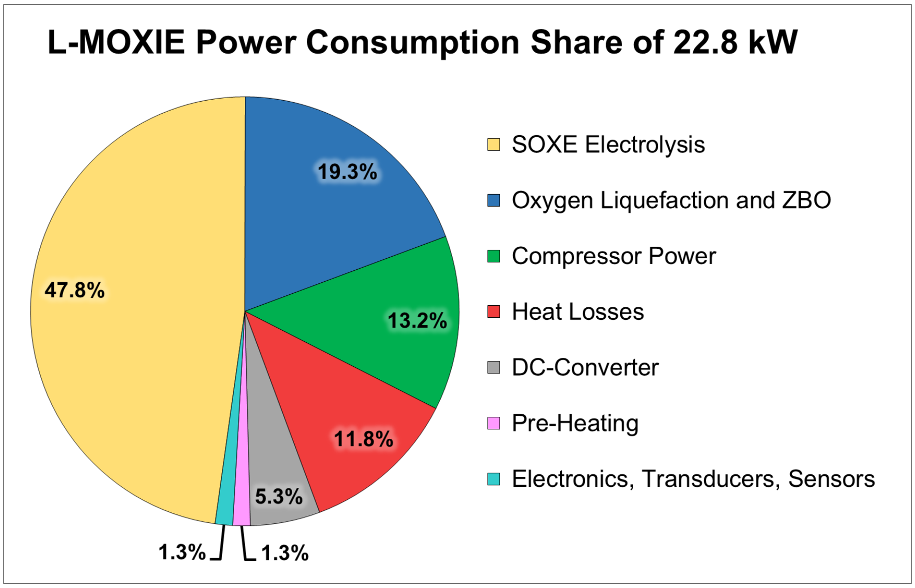

Fig. 2 Power consumption shares for the L-MOXIE operations to produce $2.22\,\mathrm{kg/h}$ **of liquefied oxygen.**

The power for the electrolysis is the major contribution in the L-MOXIE consumption. The voltage is independent from the size of the electrolyzer, while the current intensity scales linearly with productivity according to the Faraday's Laws of electrolysis. It follows that the power scales linearly. Knowing the consumption of MOXIE reported in Table 1 and the L-MOXIE productivity, a contribution of 10.8 kW is estimated. This is also confirmed by the thermodynamic calculation performed in the Aspen Hysys simulation. The compression duty is retrieved from the simulation results, summing Q_{C1} and Q_{C2}. Knowing that the compressor is a critical equipment that could bottleneck the productivity, we accounted for an additional 30% safety margin. This oversizing is independent from motor losses, mechanical losses and volumetric losses that are already included in the isentropic efficiency. The comprehensive power consumption for the two stage compression is equal to 3.0 kW. The MOXIE experiment is not equipped with any pre-heating device because of the small flowrates at stake. However, for the L-MOXIE we assumed that a FEHE is designed. This reduces the power requirements for gas pre-heating down to 0.3 kW, with a saving of 1.8 kW. The electrolyser is operated at thermal-neutral voltage of V=1.463 V meaning that the power for electrolysis is sufficient to maintain the operating temperature. The heat losses from the hot-box are estimated from the experimental data of the MOXIE test-run. We assume that the productivity is associated with device's volume while the heat losses through conduction and radiation are associated with the external surface. The MOXIE design productivity is equal to 10 g/h [5], meaning that the volume ratio is equal to 222. The area ratio is estimated through Equation 2 and it is equal to 37.

$$\left(\frac{A_{L-MOXIE}}{A_{MOXIE}}\right) = \left(\frac{V_{L-MOXIE}}{V_{MOXIE}}\right)^{0.66} \tag{2}$$

Applying this multiplier to the experimental value in Table 1, the heat losses of L-MOXIE are equal to 2.7 kW. This result is conservative because the final version of L-MOXIE could be enclosed in a more isolated box, namely an oven, to minimize the heat losses. The contribution of electronics, sensors and transducers is meaningful in the MOXIE but its impact is expected to decrease when the system is scaled-up. To estimate this contribution, we apply a conservative x10 multiplier to the value in Table 1 obtaining a power consumption of 0.3 kW. This is due to the fact that a larger system requires additional probes and sensors if some pieces of equipment are designed in series, like compressors' stages, or in parallel like the electrolysis stack. The power requirement for oxygen liquefaction and Zero Boil-Off (ZBO) system must be also fulfilled by the power generation system of the L-MOXIE. The alternatives for oxygen liquefaction on Mars are discussed by Johnson et al. [22] and among the five investigated possibilities, the tube-on-tank and tube-in-tank are the most mature technologies. From the mentioned work it results that a power consumption of 4.4 kW is needed for an oversized cryocooler to perform both the liquefaction and ZBO of a 2.22 kg/h oxygen stream. The DC-DC converter must be installed between the L-MOXIE and the Power Generation System (PGS) to allow the tuning of both current and voltage in the stack. This device dissipates part of the power produced by the PGS and a reasonable efficiency is 95%. The net power required for the L-MOXIE is the sum of all the terms previously estimated, and applying this efficiency the overall power consumption is equal to 22.8 kW. Almost half of the overall power is constituted by the requirements of the electrolyser and 19.3% is needed for the oxygen liquefaction and ZBO system. The power needed for the compression is equal to 13.2% of the total power and this proves how the compression efficiency benefits from the scale-up.

III. Methods

The methods that we employ in the design activity are described in this section. The forcing technique based on C-K theory pillars is applied to broaden the spectrum of alternatives, here called partial solutions. The partial solutions fulfill the degrees of freedom, here called functions. The generated functions and partial solutions are assembled in the morphological chart, which is used to derive three design concepts: (i) the nuclear, (ii) the grounded solar, (iii) the orbiting photovoltaic. The concepts are assessed and compared through the Multi-Attribute Utility Analysis (MAUA).

A. Forcing Technique

The C-K theory is a design theory involving a high level of abstraction, where a distinction between the space of concepts (C) and a space of knowledge (K) is introduced [23]. A set of operative tools derives from the pillars of the C-K theory and the forcing technique applied in this work is one of them. This consists of an iterative procedure aimed at enriching the K space moving between the K and C space several times. Starting from our basic knowledge in the K space, we formulate tens of possible concepts based on our spontaneous creative thinking. We investigate the crucial aspects of these first-attempt concepts and this enriches the K space. The concepts are then discarded and a new set of concepts is formulated starting from the expanded K space. This procedure is iterated several times until the K space is sufficiently wide and the iterations become ineffective.

Applying this technique we are able to generate many unexplored functions and partial solutions. This technique often introduces some elements that may lead to the generation of the so called *crazy concepts* [23], which are far from the applicability domain. However, the final design takes advantage of the knowledge expansion gained through the investigation of those unexplored alternatives during the intermediate iterations. We applied the forcing technique starting from a set of five functions: (i) the power generation technology, (ii) the power transmission, (iii) the power storage, (iv) the handling of oxygen, (v) the safety and maintenance. These functions are initially associated with few partial solutions retrieved from the personal experience of the design team. Applying the forcing technique, each function grows in a mindmap that contains additional partial solutions but also additional functions, such as the energy pathway, the location, the architecture, the storage layout, the protective devices. In the creative design framework this phase is recognized as divergent thinking [24].

B. Morphological Chart

The morphological chart is a design tool consisting in a table of functions and the associated partial solutions. The chart represented in Figure 3 is built rearranging the functions and the partial solutions that emerge from the forcing technique. As convention, the functions are listed in a column in the left hand side of the table and are labelled from A to J. The partial solutions are on the right of each function and are numbered from 1 to 8 [25]. This morphological chart provides the boundaries of our design space.

We employ the morphological chart to design the power generation concepts assigning a partial solution to each function. In the creative design framework this phase is recognized as convergent thinking [24] because from a wide design space we generate a limited number of concepts. We decide to develop three concepts with different power generation technologies, which is the function "A". This function has a greater importance compared to the others because it influences the subsequent matching of the partial solutions. The selected power generation technologies are the Kilopower reactor, the grounded solar panels and the orbiting photovoltaic panels. The Kilopower reactor is the state-of-the-art in nuclear power generation and NASA is putting a big effort in its development [6][26]. We consider the nuclear reactor, a promising technology because of its compactness, reliability and steady generation [6]. The second technology chosen by the team is a renewable source used reliably in Martian missions: the grounded solar panels. They are competitive in terms of safety and TRL, despite all the known limitations due to the intermittent solar irradiation. The third technology is chosen looking at a much longer time horizon when a colony-scale PGS could be needed. The orbiting solar panels are proposed in this framework. Even if this technology is very preliminary at the moment, the timespan between this study and a potential colonization of Mars suggests that a mature prototype could be available in 20-30 years.

	1	2	3	4	5	6	7	8
(A) POWER GENERATION	KILOPOWER	ACMIR	RTG	GROUNDED SOLAR	ORBITING SOLAR	WIND TURBINES	GEOTHERMAL	THERMAL EXCURSION
(B) ENERGY PATHWAY	THERMAL THEN ELECTRIC	ELECTRIC THEN THERMAL						
(C) LOCATION	CENTRALIZED	DISTRIBUTED						
(D) POWER TRANSMISSION	UNDER-GROUND CABLES	CABLES ON THE SURFACE	LASER POWER BEAMS	MICROWAVE POWER BEAMS	ROVERS	AERIAL VEHICLES		
(E) POWER STORAGE	CAPACITORS	RECHARGEABLE BATTERIES	COMPRESSED AIR	THERMAL	NO STORAGE			
(F) ARCHITECTURE	CENTRALIZED, COLONY SCALE	DEDICATED AND INTEGRATED	STAND ALONE, DEDICATED NOT INTEGRATED					
(G) OXYGEN STORAGE	CRYOGENIC LIQUEFACTION + ZBO	COMPRESSED GAS	REVERSIBLE ADSORBERS	CHEMICAL STORAGE AS OXIDIZER	SENSORS + WEATHER FORECAST			
(H) STORAGE LAYOUT	TANKS OF MAV	AUXILIARY TANKS						
(J) PROTECTIVE DEVICES	BLOWING FROM SURFACES	VACUUM CLEANING	UNDER-GROUND INSTALLATION	RIGID SHIELD	INFLATABLE SHIELD			

Fig. 3 Morphological chart employed to develop the three design concepts.

We generate the three concepts combining the other partial solutions looking at the affinity of each partial solution with the selected power generation technology according to our knowledge. The three morphological charts resulting from this activity are reported in Figure 4 and they act as backbones for the concepts presented in Results.

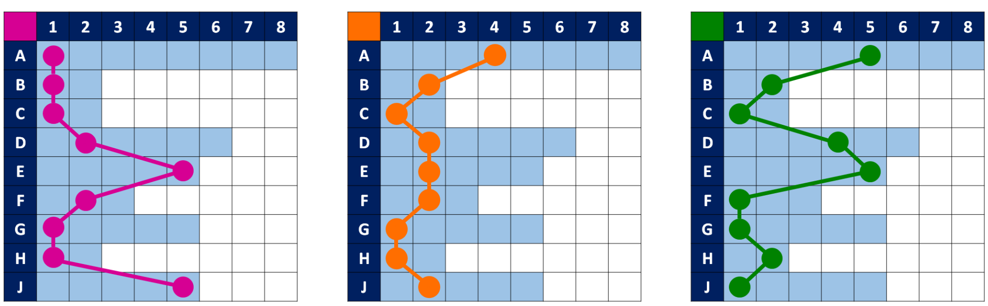

Fig. 4 Combinations of partial solutions on the morphological chart. From left to right: the nuclear concept (violet), the grounded solar concept (orange), the orbiting solar concept (green).

C. Multi-Attribute Utility Analysis

In the final part of the work we employ the Multi-Attribute Utility Analysis (MAUA) to assess the viability of the three concepts [27]. The best trade-off between technical, economic and safety requirements must be found even if a great amount of variables is involved. The variables can be commensurable or incommensurable and this complicates the problem with the risk of affecting the assessment with the designer's bias. To formalise the decision process, some useful tools have been developed by researchers in the framework of decision analysis theories. In this paper, we apply the MAUA to identify the promising alternatives among the three concepts. This method consists in mapping a multidimensional attribute space into a single-dimension preference space. This is done using the utility function U with the following properties. Considering two generic alternatives A and B:

- $U(A) > U(B)$ is A is preferred to B and
- $U(A) = U(B)$ is A and B are equally preferred
- $0 < U(x) < 1$: the utility function is assumed to vary between 0 and 1

We introduce ten metrics to assess the concepts. For each metric we assign a utility value between 1 and 0, where 1 is the best utility and 0 the worst. We determine the best design summing the weighted scores, where the weights are chosen depending on the relevance of each metric and their summation is equal to 1. The amount of mass that must be transported by the vehicle is the first metric. The highest payload mass corresponds to 0 while the lowest corresponds to 1. The mass mainly depends on the materials chosen in the design phase and on the adopted power generation technology. A weight of 0.15 (the highest) is associated to the mass since it has primary importance in the decision making process. Another metric with a 0.15 weight is the level of radiation on human body, indicating the safety level. We decided to evaluate the safety level by taking into account the crew radiation exposure. We consider the cost of development and production as important as the mass and the safety. The time required and complexity to position the system (deployability) is also an essential scoring parameter. We assign a 0.10 weight at four metrics which are the reliability of energy supply, the risk (probability of power outages and possible breakdown or damage), the compactness, and the system overall losses. The lowest weight of 0.05 is assigned to the technology readiness level (TRL), since we are considering a medium-term horizon, and to the flexibility and modularity meant as the adaptability to different landing sites.

IV. Results

A. Nuclear Concept

Figure 5 shows a schematic representation of the proposed concept while Figure 6 presents the associated deployment strategy. The nuclear kilopower reactor is characterized by the same technical features of the KRUSTY prototype [28], even though a much greater electric power has to be generated. Based on the intense research on the Kilopower technology by NASA, we assume that by the time the manned mission reaches its final state, the advancement in this technology will allow the construction of reactors able to produce up to 10 kW of electric power. Therefore, we design an array of 3 kilopower reactors with an individual power of 10 kW, to guarantee the total production of 30 kW, higher than the design basis of 22.8 kW. We assume that the reactors and the other ancillary elements, such as the battery, the zero boil-off (ZBO) system and the L-MOXIE, are pre-assembled on the Earth and shipped to Mars.

Having multiple reactors improves the reliability of the system since in case of failure of one single reactor the overall production becomes lower than the design power but it is still possible to run the other plant components. The functionality of the power sources is vital, so malfunctioning is a great concern. It is fundamental to oversize the system in order to be on the safe side to keep powering the resources even in case of failure of one or more reactors.

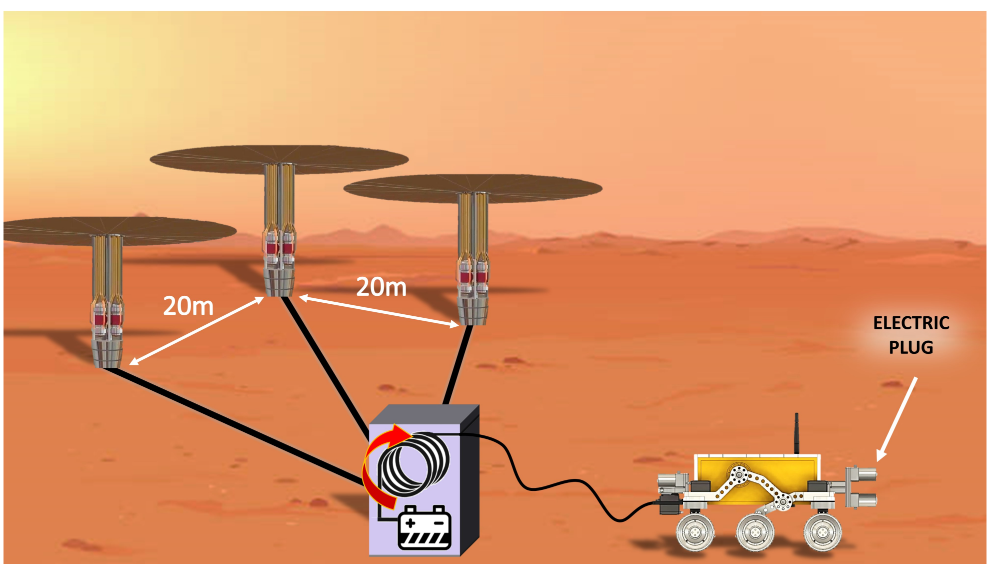

Fig. 5 Schematic diagram of reactors arrangement in the concept based on nuclear power generation system.

The materials used for these reactors are considered to be the same chosen in the experimental project. The reactor core is a cylinder of enriched Uranium, which is 6-inch diameter in the KRUSTY model. It is preferable to install the reactors below the inner Martian surface to be protected in case of hazardous events. The KRUSTY reactor was run at full power in March 2018 during a 28-hour test using a 28 kg uranium-235 reactor core [28]. A temperature of 850 °C was achieved, producing about 5.5 kW of fission power. Thus, the reactors of the nuclear concept could be similar to the KRUSTY reactor with some minor modifications. A beryllium oxide reflector surrounds the uranium core. A bar of boron carbide is used to turn the reactor on and off. The fusion reaction is self-regulated using the well-established nuclear physics technologies and no control system is needed. The heat released by fission is delivered through heat pipes to the power generators.

In the KRUSTY testing, eight heat pipes are incorporated in the assembly phase. The heat pipes start operating at around 400 °C but do not move any appreciable amounts of heat until around 600 °C. At 800 °C the heat pipes are fully operational and capable of carrying more than twice the amount of thermal energy needed to operate the Stirling engines. The power conversion system was designed for a minimum of 8 independent 125 W Stirling engines that use active balancers for vibration control. In the current concept, the number of Stirling engines would be too high to comply with the 10 kW power requirement: 80 x 125 W Stirling engines might be required. For this reason, we perform a trade-off study between the number of heat pipes and engine and the power of each Stirling device. The more powerful is the engine, the heavier and bigger it is. A possible solution could be to have 10 x 1 kW Stirling engines that, considering the whole array, would mean 30 Stirling converters in total.

Each reactor has a radiator to keep the Stirling converters cool: the KRUSTY is about 1.9 meters tall: due to the increased number of engines, it seems reasonable to increase the size of the reactor by adding two or more parallel paths. Doing so, we divide the heat pipes in 3 different blocks, 2 lateral carrying 20 pipes and a central block carrying 10 pipes. A further design optimization can be performed. This approach is interesting since it does not affect the total height of the reactor giving some consequent benefits: the wind speed is lower at lower height so less perturbation is created and less dust should impact on the reactor. Having a reactor which is not extremely high is positive for the shielding system that would be smaller and cheaper. We place the 3 reactors at a distance of about 20 meters between each other and connected to an optional small battery to flatten the fluctuations. The battery is not designed as a buffer of electric energy since the nuclear power production is not variable depending on the surrounding environment.

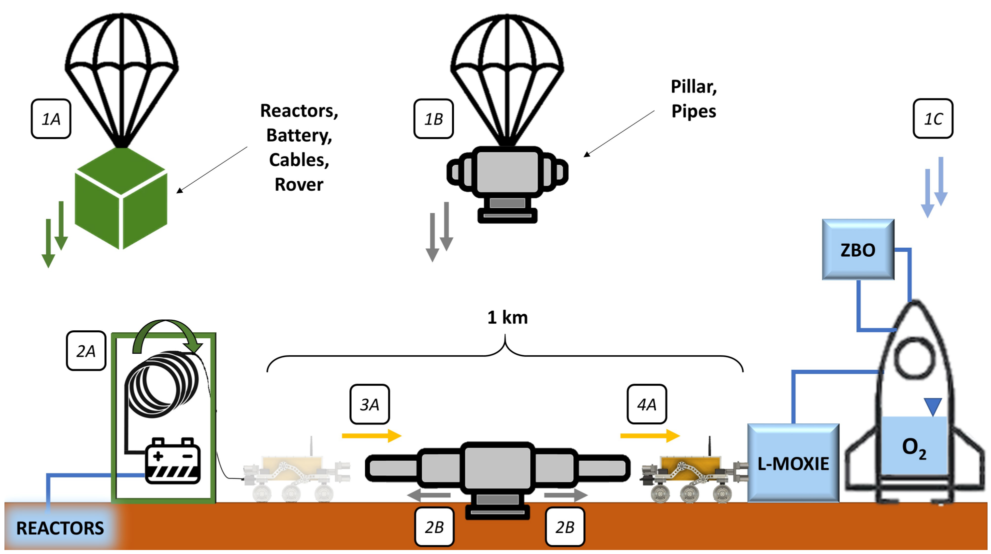

Fig. 6 Schematic representation of the deployment strategy for the nuclear design concept.
(1A) Landing of reactors, batteries, cables, rovers when packed.
(2A) Unrolling the cables that must connect the power generation system to the L-MOXIE.
(3A) The tiny rover enters the pipes and moves for a distance of 1km.
(4A) The tiny rover exits the pipes and plugs the cables into the L-MOXIE.
(1B) Landing of pillars and pipes when packed.
(2B) The pillars are stabilized and the concentric pipes are expanded.
(1C) Landing of the rocket, ZBO and L-MOXIE system.

The connections between the power generation system and the users, mainly the L-MOXIE and the ZBO system, is performed through cables. The cables are introduced inside a long pipe to protect them from the atmospheric agents. The cables are expected to be around 1 km long to ensure a sufficient distance between the nuclear reactors and the crew operating site. Being the first time that such long cables are designed for a Martian application, they are subject to lots of uncertainties linked to the stress conditions of Martian environment. For this reason, a heavier but more conservative system is designed to protect the cables not only from corrosion, but also from wind and dust. The challenge is to assemble the pipes *in situ* and use suitable high performance materials: high-chromium SS like 211HTR is used. In this concept, we build the pipes progressively by means of automated construction: an extensible pipes concept is designed. After landing, the plant is automatically build by extending pipes previously built on Earth and packed in a compact way on the MAV. AI is used to perfectly match each cable and the pipe location. Considering the long distance between the rectors and the L-MOXIE, irregularities and uneven terrain have to be carefully monitored. For this reason, we suggest to use some pillars. The construction process happens as follows: once the reactors are in the correct site, an automatic system starts to move the pillars on the Mars surface. The number of pillars and their distance is chosen based the length of the pipes contained in each pillar. Assuming that each pillar contains 250 meters of extensible pipes, around 4 pillars are used between the battery and L-MOXIE. After the positioning of the pillars, all the pipes are extended and an automated system extracts the cable from the battery-box where it is wrapped. The cable is completely deployed allowing the small automated device to internally slide through the steel pipes. In this concept, we set the oxygen tank and the zero boil-off system into the rocket to minimize the distance between the two units. The radioisotope heater units (RHU), small devices that provide heat through radioactive decay [29] [30], are used to heat the sensible points of the plant which require a minimum functioning temperature. Finally, wind shields are designed to protect the sensible components still exposed to atmospheric events such as the reactors and the L-MOXIE. They would be activated in case of storms and increased wind speed to protect the equipment from erosion or ducts clogging. The wind is measured using anemometers and if the speed is higher than a certain threshold, the shields activate an inflating balloon that is oriented towards the wind direction.

B. Grounded photovoltaic panels concept

Using the results obtained from the mission Pathfinder [31], we estimate that the minimum area of solar panels required for the continuous operation of the oxygen generator is 1400 m^2. From this rough estimation, it becomes evident that any solution proposing the design of solar panels as rover "wings" is poorly feasible. We propose the alternative solution of creating a photovoltaic power station that has an independent architecture from the MAV, as depicted in the schematic representation in Figure 7.

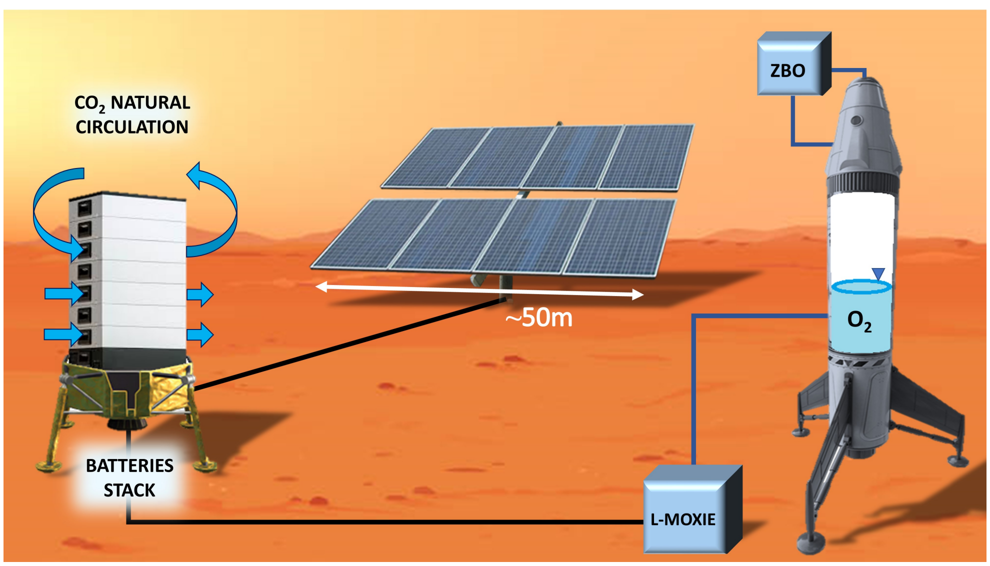

Fig. 7 Schematic representation of the design concept based on photovoltaic arrays installed on the ground.

The greatest challenge consists in the deployment of the whole system. For this purpose, we propose the introduction of some containers that are able to store the pre-assembled solar panels that, once arrived on the surface of Mars, could be moved and progressively deploy the panels on the surface in the correct position. We design two possible strategies for the deployment phase: a flexible roll of solar cells and an "accordion" configuration, as shown in Figure 8. An important feature is the convenience of using fixed or turning photovoltaic panels. The first solution leads to a much easier process of deployment, but a much more inefficient system. On the other hand, a turning photovoltaic system could maximise the solar irradiance captured, but at an incredibly higher cost in term of deployment effort: for this reason we design fixed photovoltaic panels.

The main weakness of the grounded solar panels is their dependence on the environmental conditions. In particular, the sandy soil and the frequent sandstorms can accumulate large amount of fine dust which could reduce the energy production by 70-80% according to similar data retrieved for panels on Earth [32]. From this, the necessity of a cleaning procedure. The most common method employed on Earth consists in periodical washing cycles with water, which is unfeasible on Mars due to its unavailability. Other solutions are those used in arid areas, similar to Mars in terms of constraints. While the usage of hydrophobic materials, which exploit rains to clean the surface, is inapplicable, a valid alternative is given by mechanical solutions. Consequently, we propose a microfiber-based wiper, similarly to the solution adopted by Al-Housani et al. [33], possibly associated with a vacuum cleaner. The presence of the vacuum cleaner makes the system more complex and expensive but in general more efficient. The cleaning frequency highly depends on environmental conditions, and so an optimal analysis, which weights cleaning cost and energy efficiency should be eventually carried out in loco.

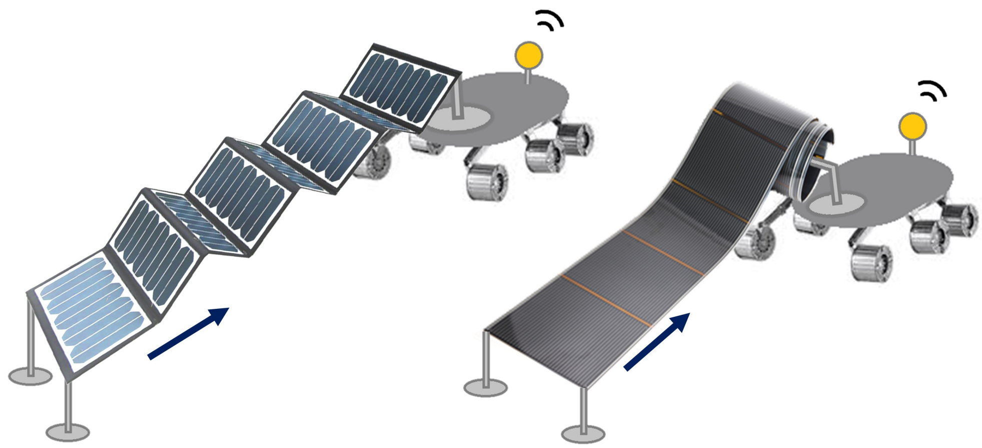

Fig. 8 Schematic representation of two possible deployment set-ups for the solar panels to ease the deployment phase.

The solar power plant under evaluation cannot produce energy continuously, so we decide to implement rechargeable batteries as power storage. This is a crucial unit in the whole power generation system because the system of batteries must satisfy the reliability and functional requirements of the mission. Moreover, it must have the highest power density possible to minimize the weight. We implement the lithium batteries which are a well-known and well-established technology in the space industry.

We decide to place all the subsystems close to each other because none of them actually constitutes a danger for the other subsystems or for human beings. However, the current batteries are not absolutely riskless, but could lead to short circuits which would generate fires and explosions. Considering that the atmosphere of Mars is mainly composed of CO_2, this phenomena would not propagate but would rather damage single components. However, we introduce the interruption valves and redundancy in power storage to mitigate these events. We propose the solution consisting in the construction of a battery stack where several small batteries are piled one over the other instead of building one single large battery. The modules are separated by open channels where the CO_2 could naturally flow, ensuring thus that sparks or fires are limited to one single element and are not affecting the whole storage system.

A network of cables connects the solar power station to the batteries and the batteries to the L-MOXIE. These cables are not too long since the subsystems are relatively close one to the other. We propose to deploy them using a small rover which pulls copper cables rolled in the subsystems themselves, moving from one subsystem to the other with a strategy similar to the one described in the nuclear concept. The connection between the L-MOXIE and the oxygen storage tank is different because some gas flows into pipes. To simplify their positioning, we place the L-MOXIE very close to the tanks to minimize their length. Moreover, we place the oxygen tank inside the MAV itself to avoid an additional complication to the system. The very low temperatures on Mars threaten the electronic devices that need dedicated heating systems to maintain the sufficient working temperature. At this scope, we introduce several electric resistances in different points, where necessary.

To sum up, the whole configuration requires approximately a surface of $1400\,\mathrm{m}^2$ of fixed solar panels which are connected to a large system of batteries. The latter would then provide energy to the L-MOXIE in a continuous way, to preserve the delicate oxygen generator from the intermittencies caused by variations in solar irradiance, storms and day-night cycles.

C. Orbiting photovoltaic panels concept

The orbiting photovoltaic panels concept is shown in Figure 9. This concept is quite futuristic and no large-scale plants are currently existing. This concept can generate multiple GW of power [34], namely five or six order of magnitudes greater than the requirements of L-MOXIE. In fact systems of smaller size would not be profitable. It follows that this concept is expected to be useful when a larger programme of Mars colonization is under development. The basic design of this power generation system consists of three elements being the orbiting solar panels, the wireless transmitter and the power receiver on the Mars surface.

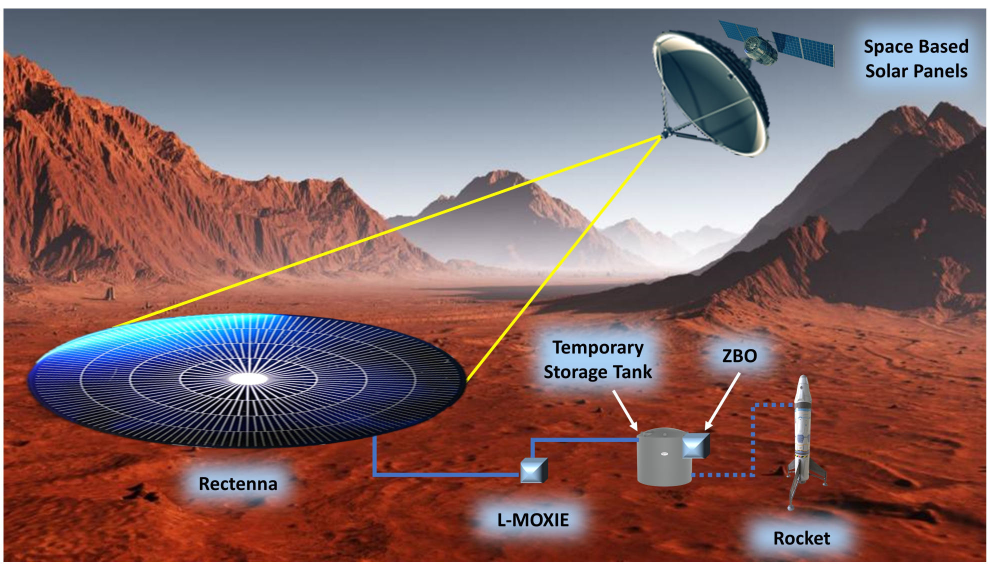

Fig. 9 Schematic representation of the design concept based on space based photovoltaic panels.

The Orbital solar panels are devoted to the collection of solar radiation in space through solar cells, improved by the use of reflectors and inflatable mirrors. We propose the most efficient solution on the market which is the multi-junction photovoltaic cell. This technology exploits a combination of several layers of indium gallium phosphide (In-Ga-P), gallium arsenide (Ga-As) and germanium (Ge) to collect a wider power distribution from the solar spectrum. To reduce the weight, we propose the usage of thin-film photovoltaic cells, flexible blanket substrates and composite support structures.

The Wireless Power Transmission to the ground base is performed via microwave, radio waves or laser. The concept that we propose is based on the overview carried out by Wood [35]. The system is designed to work in the areostationary orbit (AEO) [36]. The power is transmitted via electromagnetic waves at 2.45 GHz (radio waves) to dedicated receiver stations on the ground, called "rectennas", which convert the energy back into electricity used in the local grid. The rectenna consists of many short dipole antennas connected via diodes which reduces the costs and complexity of the system. Overall, the rectenna is a circle with a very large diameter, in the order of kilometers, to be assembled on Mars surface [37]. The evolution of this transmission technology is expected to improve the theoretical transmission efficiencies via electromagnetic waves, arising to 50-60%. One main challenge for the space-based solar power satellite is the construction of large structures in orbit. Not only they require a significant amount of materials to be launched into space, but they need to be assembled, maintained and possibly replaced over time. Due to the harsh space environment, the lifetime of current solar panels in space is significantly shorter compared to the ones installed on the surface.

The connection of the power source to the oxygen generation system is not affected by evident constraints and for these reasons, we place the L-MOXIE close to the receiving antenna. Concerning the storage of oxygen, we propose to keep the liquefied fluid in a dedicated tank not embedded into the rocket, with its own ZBO system. We make this decision because the construction of this PGS is considered as a long term investment and, once the whole set-up is installed, it could be run for several Mars missions belonging to the same programme, producing thus the oxygen for a MAV that is not yet arrived on the red planet. The oxygen needs to be transported from the storage tank to the the rocket through a network of pipes, valves and regulators only when the rocket needs to be loaded for the return voyage. We design a system of pipes that allow also the redeployment of the oxygen for different functions, such as breathing apparatus for humans. We propose a set of blowers to remove the dust from the working surface.

The main advantage of the wireless power transmission consist in the possibility to deliver electricity to any location on the planet without a large-scale interconnected grid. In this way it is possible to dynamically allocate power into the new regions where it is required, in prevision of colonies development [38].

D. Concepts Assessment

We assess the three concepts presented in this work by means of the Multi-Attribute Utility Analysis (MAUA). The results of this analysis are reported in Table 3, and we explain the reason why certain scores are given as following.

1) **Mass**: the mass of a single kilopower reactor is 2751 kg [26] and with 3 units the total payload mass is 8253 kg. For the grounded solar system, as a first rough estimation, we assume that the panels can generate power only half sol, and the rest of the time the energy is provided to L-MOXIE through the batteries. This means that the panels are sized for 50 kW. An average power to mass ratio of solar cells is 80 W/kg [39], meaning that 625 kg of solar panels are required. The battery weight is evaluated considering an energy to weight ratio of 100 Wh/kg [40], and an amount of energy to be stored of 300 kW h, which is half of the L-MOXIE daily requirements. This means an additional weight of 3000 kg. The overall payload of the grounded solar system is 3625 kg. The orbiting photovoltaic system is the heavier of the three. The microwave transmitting satellite, with 1 km of transmitting antenna, is estimated to be about 80,000 tons which makes this solution incomparable with the others. A value of 1 is assigned to the grounded solar system, 0.44 to the nuclear, and 0.01 to the orbiting photovoltaic.
2) **Safety**: the solar technology does not emit ionizing radiations, for this reason a value of 1 can be assigned to both solar concepts. A value of 0.8 is considered for the kilopower, with less than 3 mR/hr (millirem per hour) within 500 meters [41].
3) **Deployability**: the grounded solar consists in a larger amount of cables to cover a shorter distance, while the kilopower deployement is developed thanks to a smaller amount of cables but on a longer distance. Therefore, we assigned 1 to both nuclear and grounded solar concept. The orbiting solar has instead a complex deployability and we assigned a value of 0.6.
4) **Reliability of energy supply**: a value of 1 is assigned to the kilopower because it is able to produce energy independently of the environmental conditions. On the other hand, a value of 0.75 is assigned to the solar solutions whose energy production capabilities depends on the environmental conditions.
5) **Risk**: a value of 1 is assigned to the nuclear concept, while for the grounded 0.9 and for orbiting solar 0.8, due its critical working environment.
6) **Compactness**: regarding the kilopower, an approximate volume of 25 m^3 must be transported on the vehicle, considering 4 m height and 1.5 m diameter [42]. In the case of the grounded solar system the volume for transportation is given by the panels and the batteries. The average thickness is assumed equal to 3.5 mm [39] and considering a surface of 1400 m^2, the total volume is around 5 m^3. For the batteries the power to volume ratio is around 250 $kW\,h\,m^{-3}$ [40] meaning a battery of 1.2 m^3. Including the cabling systems we assume a total transportation volume of 10 m^3. In the case of the solar orbiting photovoltaic system, very large antennas are needed and an arbitrary value of 0.01 is assigned. The value of 1 is assigned to the grounded solar system and a value of 0.4 to the nuclear concept proportionally to the weight.
7) **TRL**: TRL 5 is assumed for the kilopower in the current application [41]. A value of 1 is assigned to the grounded solar because it is the most mature technology. The values of 0.7 and 0.3 are chosen for the nuclear and orbiting solar respectively.
8) **Flexibility and Modularity**: based on the team evaluation, a value of 1 is assigned to the kilopower, and 0.75 to

the grounded solar. 0.85 is chosen for the orbiting solar technology.

9) **Cost**: the kilopower reactor has higher research and development cost compared to the grounded solar. Based on this, A value of 1 is assigned to the solar solution, 0.75 to the kilopower and 0.3 to the orbiting solar because the system needs to be largely developed.
10) **Losses**: for the kilopower reactor, losses from heat pipes, engines and structures must be considered as well as core thermal power losses. The whole production is decreased of about 2-3% [6]. For the grounded solar system losses are given by the Joule effect of the current running through the cables and the losses linked to the batteries themselves. The first ones can be neglected as the wiring is very short, and the second one is very small for a day-to-day cycle. For this reason a value of 1 is given to the solar systems and a value of 0.97 is given to the nuclear concept.

Evaluation Metrics	Concept 1: Nuclear	Concept 2: Grounded Solar	Concept 3: Orbiting Solar	Weight
Mass	0.44	1	0.01	0.15
Safety	0.8	1	1	0.15
Deployability	1	1	0.6	0.05
Reliability of energy supply	1	0.75	0.75	0.10
Risk	1	0.9	0.8	0.10
Compactness	0.4	1	0.01	0.10
Technology readiness level (TRL)	0.7	1	0.3	0.05
Flexibility and Modularity	1	0.75	0.85	0.05
Cost	0.75	1	0.3	0.15
Losses	0.97	1	1	0.10
Total	0.77	0.95	0.54	

Table 3 Results of the Multi-Attribute Utility Analysis of the three concepts

V. Conclusions

Starting from the experimental data of MOXIE and the simulation of L-MOXIE, we estimate an overall power consumption of 22.8 kW comprehending also the oxygen liquefaction section. This is slightly lower than previous estimations and in particular the compressors requirements drive this trend. Focusing strictly on the L-MOXIE, the power consumption breakdown reported in this work is a powerful tool to understand the items that need greater attention in the conceptual and mechanical design of the scaled-up generator to minimize the power consumption of the system. Leveraging the forcing technique and the morphological chart, we generate three concepts for the power generation system, based on nuclear reactors, grounded solar panels, orbiting solar panels. According to our design, the nuclear concept includes 3 kilopower reactors with a size of 10 kW each. This system is expected to work in continuous without any energy storage. The kilopower reactors must be installed around 500 m from the human settlement for safety reasons. The cabling between the reactor and the L-MOXIE, that should be installed next to the MAV, requires special attention and we propose a system constituted by deployable tubes. To protect the reactors from sandstorm we propose an inflatable shielding system. The concept based on grounded solar panels has a smaller plot because it is not necessary to separate the power generation system from the MAV. We estimate the area of the solar panels to be 1400 m^2 and we propose a configuration with rolled or "accordion" panels to ease the deployability. We propose the usage of a batteries to allow a continuous functioning of L-MOXIE. The concept based on orbiting solar panels has a low TRL and according to the results that we obtained through the MAUA, it is not convenient. However it gives good insights for the possible power generation system of a future human colony on Mars. The overall assessment resulting from the MAUA depend on the given scores, but the result obtained would be the same even in case of slight modifications. In fact, having ten different metrics and an even distribution of the weights, we consider the assessment to be robust. Our work is a proper benchmark for the comparison of different Power Generation Systems and useful insights are provided for space agencies and external institutions.

This study sets the ground for a number of future follow-up activities after the project is over. The simulation of L-MOXIE can be re-developed using the experimental data coming from the *Mars2020* mission instead of the experimental data gathered in the controlled environment of NASA Jet Propulsion Laboratory. This future simulation would give more robust results with few effort, since it employs the same methods already developed in this work. A second follow-up is the development of a feasibility analysis for the proposed concepts. This allows a better estimation of the weights and volumes at stake of the proposed concepts. A multi-objective optimization can be performed both for the nuclear and grounded solar concept starting from the scheme proposed in this work. Concerning the orbiting solar concept, a follow-up activity consists in the estimation of the size and weight of the main antennas for a pre-feasibility study. As a last point, it is worth deepening the possible synergies of the power generation system with other energy-intensive devices that will be used in future missions on Mars.

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